

Transverse Momentum Dependent Gluon Distributions at an EIC

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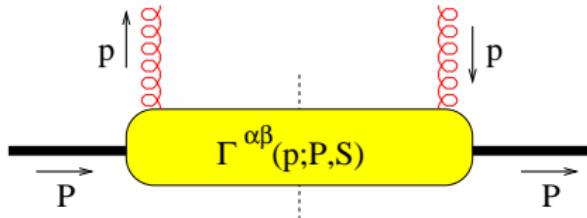
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The gluon correlator describes the hadron \rightarrow gluon transition



Gluon momentum $p^\alpha = x P^\alpha + p_T^\alpha + p^- n^\alpha$, with $n^2=0$ and $n \cdot P \neq 0$

Spin vector: $S^\alpha = \frac{S_L}{M_h} \left(P^\alpha - \frac{M_h^2}{P \cdot n} n^\alpha \right) + S_T$, with $S_L^2 + S_T^2 = 1$

Definition of $\Gamma^{\alpha\beta}$ for a spin-1/2 hadron

$$\Gamma^{\alpha\beta} = \frac{n_\rho n_\sigma}{(P \cdot n)^2} \int \frac{d(\xi \cdot P)}{(2\pi)^3} d\xi_T e^{ip \cdot \xi} \langle P, S | \text{Tr} [F^{\alpha\rho}(0) U_{[0,\xi]} F^{\beta\sigma}(\xi) U'_{[\xi,0]}] | P, S \rangle \Big|_{\xi \cdot n = 0}$$

Mulders, Rodrigues, PRD 63 (2001) 094021

U, U' : process dependent gauge links

Transverse projectors: $g_T^{\alpha\beta} \equiv g^{\alpha\beta} - P^\alpha n^\beta - n^\alpha P^\beta$, $\epsilon_T^{\alpha\beta} \equiv \epsilon^{\alpha\beta\gamma\delta} P_\gamma n_\delta$

Parametrization of $\Gamma^{\alpha\beta}$ (at “Leading Twist” and omitting gauge links)

$$\Gamma_U^{\alpha\beta}(x, \mathbf{p}_T) = \frac{x}{2} \left\{ -g_T^{\alpha\beta} f_1^g(x, \mathbf{p}_T^2) + \left(\frac{p_T^\alpha p_T^\beta}{M_h^2} + g_T^{\alpha\beta} \frac{\mathbf{p}_T^2}{2M_h^2} \right) h_1^{\perp g}(x, \mathbf{p}_T^2) \right\} \text{ [unp. hadron]}$$

Mulders, Rodrigues, PRD 63 (2001) 094021
Meissner, Metz, Goeke, PRD 76 (2007) 034002

- ▶ f_1^g : unpolarized TMD gluon distribution
- ▶ $h_1^{\perp g}$: T -even distribution of linearly polarized gluons inside an unp. hadron

Parametrization of $\Gamma^{\alpha\beta}$ (at “Leading Twist” and omitting gauge links)

$$\begin{aligned}\Gamma_T^{\alpha\beta}(x, \mathbf{p}_T) = & \frac{x}{2} \left\{ g_T^{\alpha\beta} \frac{\epsilon_T^{\rho\sigma} p_{T\rho} S_{T\sigma}}{M_h} f_{1T}^{\perp g}(x, \mathbf{p}_T^2) + i \epsilon_T^{\alpha\beta} \frac{\mathbf{p}_T \cdot \mathbf{S}_T}{M_h} g_{1T}^g(x, \mathbf{p}_T^2) \right. \\ & - \frac{p_{T\rho} \epsilon_T^{\rho\{\alpha} S_T^{\beta\}} + S_{T\rho} \epsilon_T^{\rho\{\alpha} p_T^{\beta\}}}{4M_h} h_{1T}^g(x, \mathbf{p}_T^2) + \frac{p_{T\rho} \epsilon_T^{\rho\{\alpha} p_T^{\beta\}}}{2M_h^2} \frac{\mathbf{p}_T \cdot \mathbf{S}_T}{M_h} h_{1T}^{\perp g}(x, \mathbf{p}_T^2) \left. \right\} \\ & \quad [\text{transv. pol. hadron}]\end{aligned}$$

Mulders, Rodrigues, PRD 63 (2001) 094021
Meissner, Metz, Goeke, PRD 76 (2007) 034002

- ▶ $f_{1T}^{\perp g}$: T -odd distributions of unp. gluons inside a transversely pol. hadron
- ▶ h_{1T}^g , $h_{1T}^{\perp g}$: helicity flip distributions like h_{1T}^q , $h_{1T}^{\perp q}$, but T -odd, chiral even!

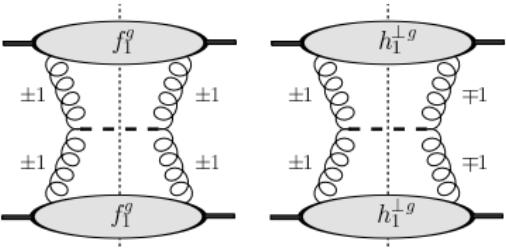
Transversity $h_1^q \equiv h_{1T}^q + \frac{\mathbf{p}_T^2}{2M_p^2} h_{1T}^{\perp q}$ survives under p_T integration, unlike h_1^g

Gluon polarization and the Higgs boson

$p p \rightarrow H X$ at the LHC

The dominant production channel is $gg \rightarrow H$

$h_1^{\perp g}$ contributes to the q_T -spectrum at LO



q_T -distribution of the Higgs boson

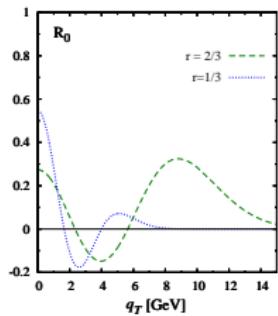
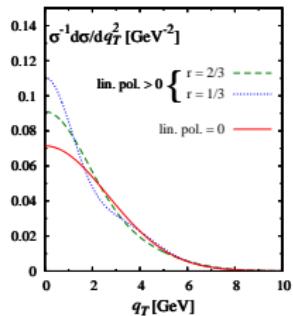
$$\frac{1}{\sigma} \frac{d\sigma}{dq_T^2} \propto 1 + R(q_T^2)$$

$$R = \frac{h_1^{\perp g} \otimes h_1^{\perp g}}{f_1^g \otimes f_1^g}$$

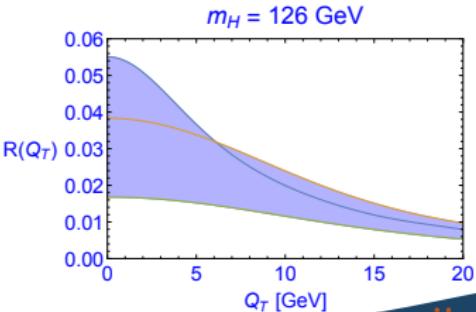
$$|h_1^{\perp g}(x, p_T^2)| \leq \frac{2M_p^2}{p_T^2} f_1^g(x, p_T^2)$$

Boer, den Dunnen, CP, Schlegel, Vogelsang, PRL 108 (2012) 032002
 Boer, den Dunnen, CP, Schlegel, PRL 111 (2013) 032002
 Echevarria, Kasemets, Mulders, CP, JHEP 1507 (2015) 158

Gaussian Model



TMD evolution



Study of $H \rightarrow \gamma\gamma$ and interference with $gg \rightarrow \gamma\gamma$

$C = +1$ quarkonium production

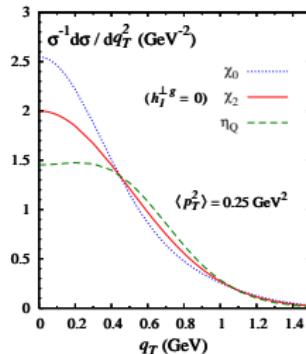
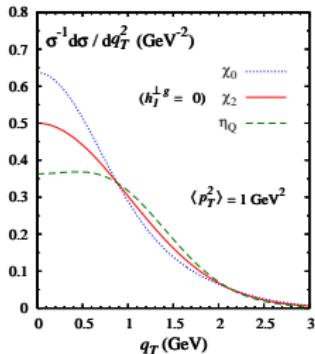
q_T -distribution of η_Q and χ_{QJ} ($Q = c, b$) in the kinematic region $q_T \ll 2M_Q$

$$\frac{1}{\sigma(\eta_Q)} \frac{d\sigma(\eta_Q)}{d\mathbf{q}_T^2} \propto f_1^g \otimes f_1^g [1 - R(\mathbf{q}_T^2)] \quad [\text{pseudoscalar}]$$

$$\frac{1}{\sigma(\chi_{Q0})} \frac{d\sigma(\chi_{Q0})}{d\mathbf{q}_T^2} \propto f_1^g \otimes f_1^g [1 + R(\mathbf{q}_T^2)] \quad [\text{scalar}]$$

$$\frac{1}{\sigma(\chi_{Q2})} \frac{d\sigma(\chi_{Q2})}{d\mathbf{q}_T^2} \propto f_1^g \otimes f_1^g$$

Boer, CP, PRD 86 (2012) 094007



Proof of factorization at NLO for $p p \rightarrow \eta_Q X$ in the Color Singlet Model (CSM)

Ma, Wang, Zhao, PRD 88 (2013), 014027; PLB 737 (2014) 103

Study of $p p \rightarrow \eta_c X$ at NLO with TMD evolution (LHCb data)

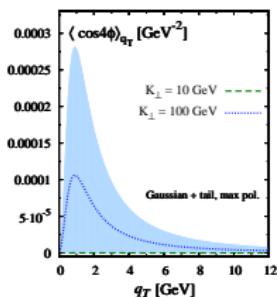
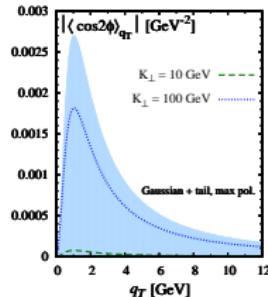
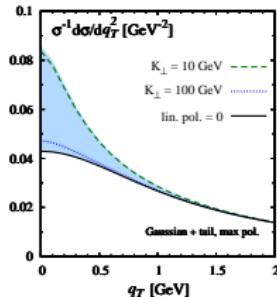
Echevarria, Kasemets, Lansberg, CP, Signori, *in preparation* (2016)



Azimuthal asymmetries at the LHC

$p p \rightarrow H \text{ jet } X$ and $p p \rightarrow J/\psi \gamma X$

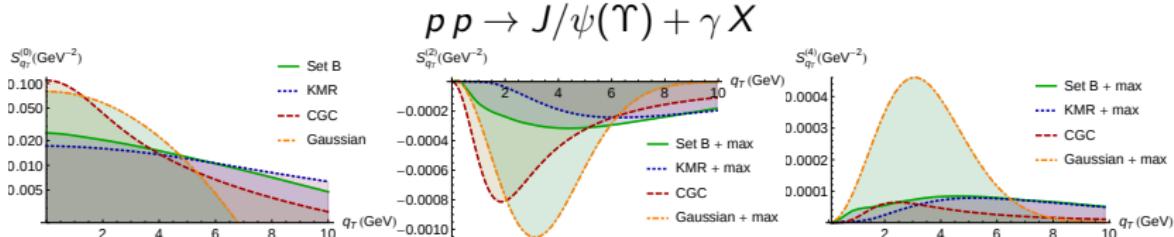
$p p \rightarrow H + \text{jet } X$



Boer, CP, PRD 91 (2015) 074024

$$\frac{1}{\sigma} \frac{d\sigma}{d^2 q_T} \equiv S_{q_T}^{(0)} \equiv \langle 1 \rangle_{q_T} \implies f_1^g \otimes f_1^g \quad [+ h_1^{\perp g} \otimes h_1^{\perp g} \text{ in } H + \text{jet}]$$

$$S_{q_T}^{(2)} \equiv \langle \cos 2\phi \rangle_{q_T} \implies f_1^g \otimes h_1^{\perp g} \quad S_{q_T}^{(4)} \equiv \langle \cos 4\phi \rangle_{q_T} \implies h_1^{\perp g} \otimes h_1^{\perp g}$$



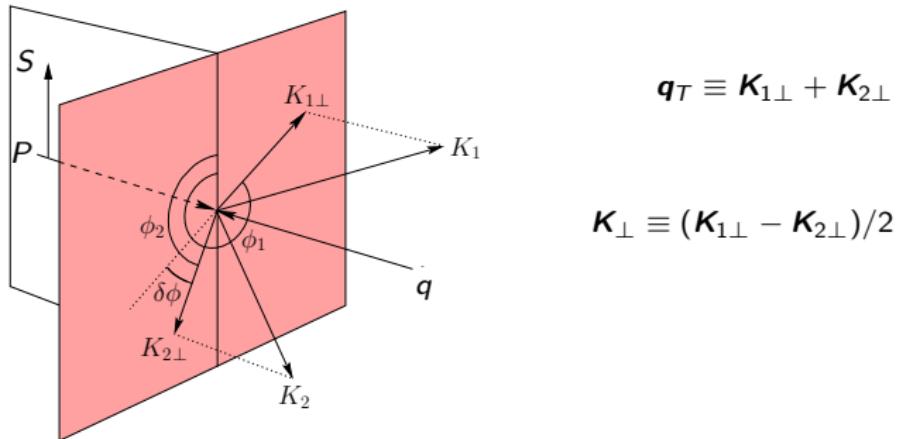
den Dunnen, Lansberg, CP, Schlegel, PRL 112 (2014) 212001

Heavy quark pair production in DIS Kinematics

Gluon TMDs probed directly in $e(\ell) + p(P, S) \rightarrow e(\ell') + Q(K_1) + \bar{Q}(K_2) + X$

Boer, Mulders, CP, Zhou, JHEP 1608 (2016) 001

- ▶ the $Q\bar{Q}$ pair is almost back to back in the plane \perp to q and P
- ▶ $q \equiv \ell - \ell'$: four-momentum of the exchanged virtual photon γ^*



➡ Correlation limit: $|q_T| \ll |K_\perp|$, $|K_\perp| \approx |K_{1\perp}| \approx |K_{2\perp}|$

Heavy quark pair production in DIS

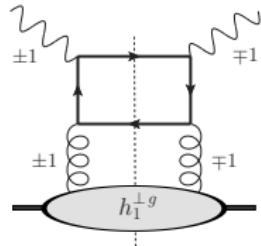
Angular structure of the cross section

y_1 (y_2) rapidities of Q (\bar{Q}) in the $\gamma^* p$ cms; x_B, y : DIS variables

$$\mathbf{q}_T \equiv \mathbf{K}_{1\perp} + \mathbf{K}_{2\perp} = |\mathbf{q}_T|(\cos \phi_T, \sin \phi_T)$$

$$K_{\perp} \equiv (K_{1\perp} - K_{2\perp})/2 = |K_{\perp}|(\cos \phi_{\perp}, \sin \phi_{\perp})$$

$$S_T = S_T(\cos \phi_S, \sin \phi_S) \text{ in a frame where } \phi_{\ell} = \phi_{\ell'} = 0$$



At LO in pQCD: only $\gamma^* g \rightarrow Q\bar{Q}$ contributes

$$d\sigma(\phi_S, \phi_T, \phi_{\perp}) = d\sigma^U(\phi_T, \phi_{\perp}) + d\sigma^T(\phi_S, \phi_T, \phi_{\perp})$$

Angular structure of the unpolarized cross section for $e p \rightarrow e' Q\bar{Q} X$, $|\mathbf{q}_T| \ll |\mathbf{K}_{\perp}|$

$$\begin{aligned} \frac{d\sigma^U}{dy_1 dy_2 dy dx_B d^2 \mathbf{q}_T d^2 \mathbf{K}_{\perp}} &\propto \left\{ A_0^U + A_1^U \cos \phi_{\perp} + A_2^U \cos 2\phi_{\perp} \right\} f_1^g(x, \mathbf{q}_T^2) + \frac{\mathbf{q}_T^2}{M_p^2} h_1^{\perp g}(x, \mathbf{q}_T^2) \\ &\times \left\{ B_0^U \cos 2\phi_T + B_1^U \cos(2\phi_T - \phi_{\perp}) + B_2^U \cos 2(\phi_T - \phi_{\perp}) + B_3^U \cos(2\phi_T - 3\phi_{\perp}) + B_4^U \cos 2(\phi_T - 2\phi_{\perp}) \right\} \end{aligned}$$

The different contributions can be isolated by defining

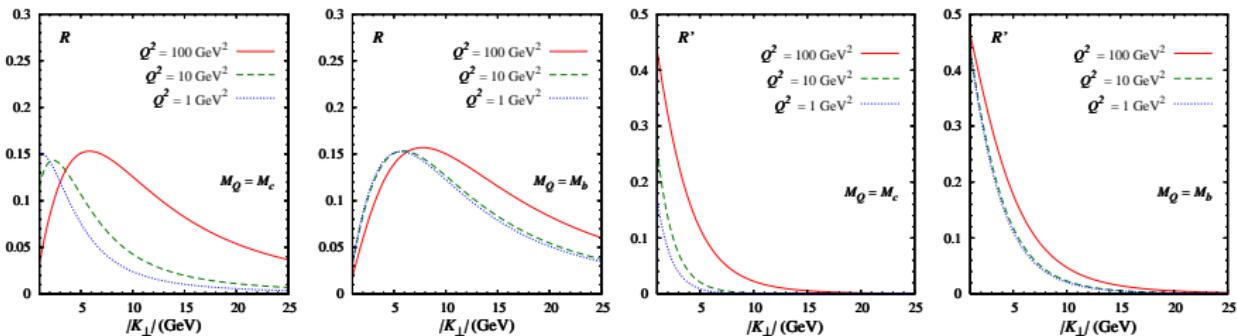
$$\langle W(\phi_{\perp}, \phi_T) \rangle = \frac{\int d\phi_{\perp} d\phi_T W(\phi_{\perp}, \phi_T) d\sigma}{\int d\phi_{\perp} d\phi_T d\sigma}, \quad W = \cos 2\phi_T, \cos 2(\phi_{\perp} - \phi_T), \dots$$

Positivity bound for $h_1^{\perp g}$: $|h_1^{\perp g}(x, \mathbf{p}_T^2)| \leq \frac{2M_p^2}{\mathbf{p}_T^2} f_1^g(x, \mathbf{p}_T^2)$

It can be used to estimate maximal values of the asymmetries

Asymmetries usually larger when Q and \bar{Q} have same rapidities

Upper bounds on $R \equiv |\langle \cos 2(\phi_T - \phi_\perp) \rangle|$ and $R' \equiv |\langle \cos 2\phi_T \rangle|$ at $y = 0.01$



CP, Boer, Brodsky, Buffing, Mulders, JHEP 1310 (2013) 024
 Boer, Brodsky, Mulders, CP, PRL 106 (2011) 132001

SSAs in $ep^\uparrow \rightarrow e' Q\bar{Q}X$

Angular structure of the single polarized cross section for $ep^\uparrow \rightarrow e' Q\bar{Q}X$, $|\mathbf{q}_T| \ll |\mathbf{K}_\perp|$

$$\begin{aligned} d\sigma^T \propto & \sin(\phi_S - \phi_T) \left[A_0^T + A_1^T \cos \phi_\perp + A_2^T \cos 2\phi_\perp \right] f_{1T}^{\perp g} + \cos(\phi_S - \phi_T) \left[B_0^T \sin 2\phi_T \right. \\ & + B_1^T \sin(2\phi_T - \phi_\perp) + B_2^T \sin 2(\phi_T - \phi_\perp) + B_3^T \sin(2\phi_T - 3\phi_\perp) + B_4^T \sin(2\phi_T - 4\phi_\perp) \Big] h_{1T}^{\perp g} \\ & + \left[B_0'^T \sin(\phi_S + \phi_T) + B_1'^T \sin(\phi_S + \phi_T - \phi_\perp) + B_2'^T \sin(\phi_S + \phi_T - 2\phi_\perp) \right. \\ & \left. + B_3'^T \sin(\phi_S + \phi_T - 3\phi_\perp) + B_4'^T \sin(\phi_S + \phi_T - 4\phi_\perp) \right] h_{1T}^{g} \end{aligned}$$

The ϕ_S dependent terms can be singled out by means of azimuthal moments A_N^W

$$A_N^{W(\phi_S, \phi_T)} \equiv 2 \frac{\int d\phi_T d\phi_\perp W(\phi_S, \phi_T) d\sigma_T(\phi_S, \phi_T, \phi_\perp)}{\int d\phi_T d\phi_\perp d\sigma_U(\phi_T, \phi_\perp)}$$

$$A_N^{\sin(\phi_S - \phi_T)} \propto \frac{f_{1T}^{\perp g}}{f_1^g} \quad A_N^{\sin(\phi_S + \phi_T)} \propto \frac{h_1^g}{f_1^g} \quad A_N^{\sin(\phi_S - 3\phi_T)} \propto \frac{h_{1T}^{\perp g}}{f_1^g}$$

Same modulations as in SIDIS for quark TMDs ($\phi_T \rightarrow \phi_h$)

Boer, Mulders, PRD D57 (1998) 5780

Omitted factors in $A_N^{\sin(\phi_S - 3\phi_T)}$, $A_N^{\sin(\phi_S + \phi_T)} \rightarrow 0$ if $y \rightarrow 1$ ($x \rightarrow 0$ if $s/Q^2 \rightarrow \infty$)

$$\frac{A_N^{\sin(\phi_S - 3\phi_T)}}{A_N^{\sin(\phi_S + \phi_T)}} = -\frac{q_T^2}{2M_p^2} \frac{h_{1T}^{\perp g}}{h_1^g}$$

direct probe of the relative magnitude of the two TMDs

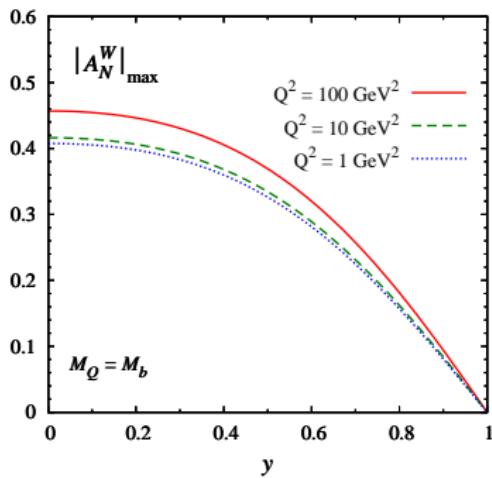
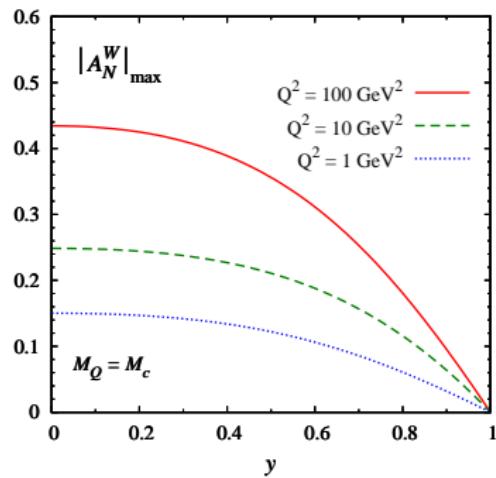
Alternatively, azimuthal angles defined w.r.t. ϕ_\perp instead of ϕ_ℓ (integrated over) $A_N^{W_\perp}$ with $W_\perp = \sin(\phi_S^\perp - \phi_T^\perp), \sin(\phi_S^\perp + \phi_T^\perp), \sin(\phi_S^\perp - 3\phi_T^\perp)$

Positivity bounds of T -odd gluon TMDs used to estimate maximal SSAs

$$\frac{|\boldsymbol{p}_T|}{M_p} |f_{1T}^{\perp g}| \leq f_1^g \quad \frac{|\boldsymbol{p}_T|}{M_p} |h_1^g| \leq f_1^g \quad \frac{|\boldsymbol{p}_T|^3}{2M_p^3} |h_{1T}^{\perp g}| \leq f_1^g$$

Upper bound of the Sivers asymmetries is 1

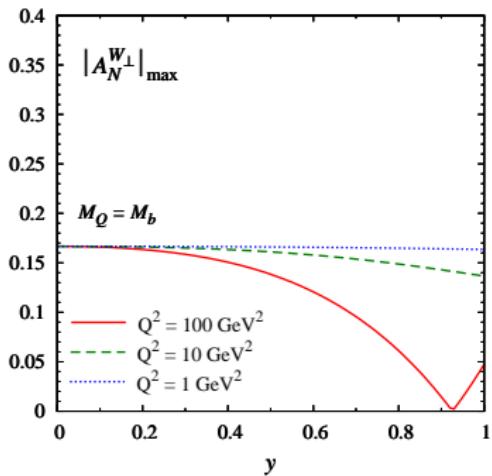
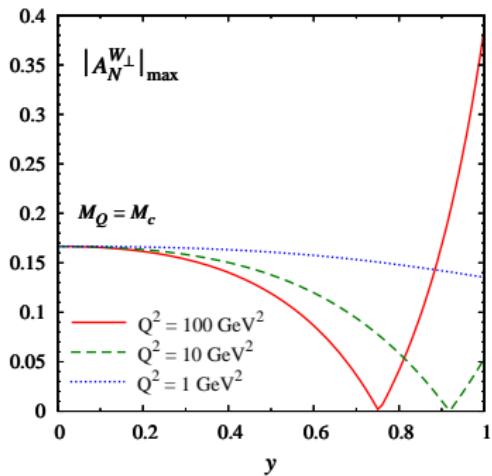
Maximal values for $|A_N^W|$, $W = \sin(\phi_S + \phi_T)$, $\sin(\phi_S - 3\phi_T)$ ($|\mathbf{K}_\perp| = 1$ GeV)



SSAs $A_N^{W_\perp}$ in $ep^\dagger \rightarrow e' Q \bar{Q} X$

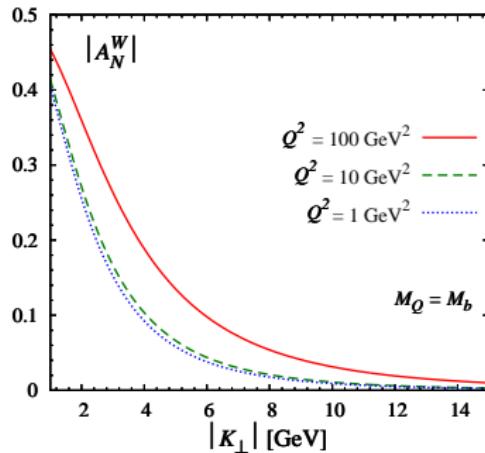
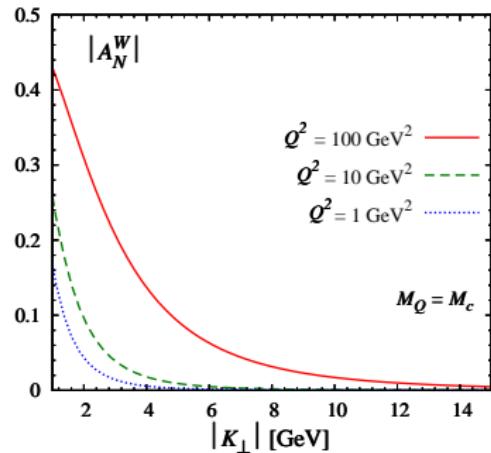
Upper bounds

Maximal values for $|A_N^{W_\perp}|$, $W_\perp = \sin(\phi_S^\perp + \phi_T^\perp), \sin(\phi_S^\perp - 3\phi_T^\perp)$ ($|\mathcal{K}_\perp| = 1$ GeV)

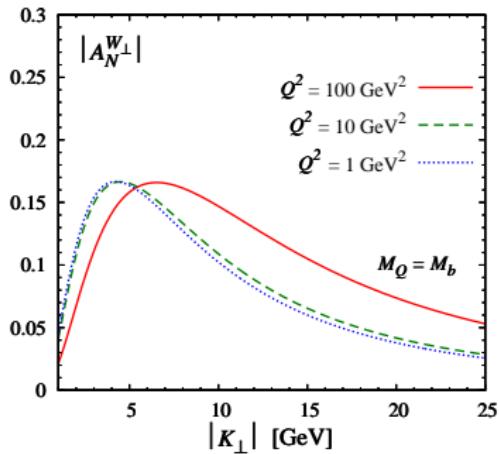
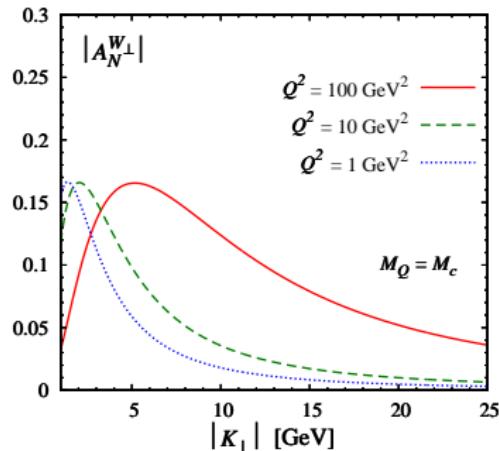


$|A_N^{W_\perp}|$ do not vanish when $y \rightarrow 0$, zero crossing

$|A_N^W|$ vs $|K_\perp|$ at $y = 0.1$; same upper bounds as $|\langle \cos 2\phi_T \rangle|$



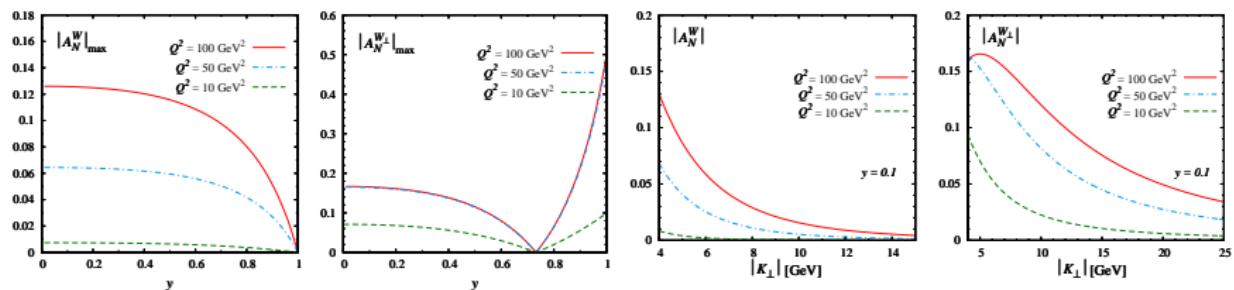
$|A_N^{W\perp}|$ vs $|K_\perp|$ at $y = 0.1$; same upper bounds as $|\langle \cos 2(\phi_T - \phi_\perp) \rangle|$



Results can be obtained by taking $M_Q = 0$ in the expressions for $ep \rightarrow e' Q \bar{Q} X$

Contribution to the denominator also from $\gamma^* q \rightarrow gq$, negligible at small- x

Upper bounds for A_N^W and $A_N^{W\perp}$ for $|K_\perp| \geq 4$ GeV



Asymmetries much smaller than in $c\bar{c}$ case for $Q^2 \leq 10$ GeV 2

Complementary Processes

$ep \rightarrow e' Q\bar{Q}X$, $ep \rightarrow e'$ jet jet X probe gluon TMDs with [++) gauge links (**WW**)

$pp \rightarrow \gamma$ jet X probes an entirely independent gluon TMD: [+−] links (**dipole**)

Talk by D. Boer

Related Processes

In $pp \rightarrow \gamma\gamma X$ and/or other CS final state: gluon TMDs have [−−] gauge links

Qiu, Schlegel, Vogelsang, PRL 107 (2011) 062001

Analogue of the sign change of $f_{1T}^{\perp g}$ between SIDIS and DY (true also for h_1^g and $h_{1T}^{\perp g}$)

$$f_{1T}^{\perp g} [e p^\uparrow \rightarrow e' Q\bar{Q} X] = -f_{1T}^{\perp g} [p^\uparrow p \rightarrow \gamma\gamma X]$$

Motivation to study the gluon Sivers effect at RHIC and AFTER@LHC

Brodsky, Fleuret, Hadjidakis, Lansberg, Phys. Rept. 522 (2013) 239

T-even gluon TMDs probed in DIS are the same as in $pp \rightarrow H/\eta_{c,b}/...X$

$$h_1^{\perp g} [e p \rightarrow e' Q\bar{Q} X] = h_1^{\perp g} [p p \rightarrow H X]$$

TMD observables at EIC and LHC can be either related or complementary

- ▶ Azimuthal asymmetries in heavy quark pair and dijet production in DIS could probe WW-type gluon TMDs (similar to SIDIS for quark TMDs)
- ▶ Asymmetries maximally allowed by positivity bounds of gluon TMDs can be sizeable in specific kinematic region
- ▶ Study of TMDs and asymmetries in the small- x region

Talk by D. Boer

- ▶ Different behaviour of WW and dipole gluon TMDs accessible at RHIC could be tested experimentally
- ▶ Such observables could be part of both the *spin* and the *small-x* program at a future EIC